Hydrological cycle amplification overwhelms warming-driven oxygen loss in subsurface Atlantic Ocean

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Hydrological cycle amplification overwhelms warming-driven oxygen loss in subsurface Atlantic Ocean

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ABSTRACT: The global ocean is losing oxygen due to warming, which is expected to significantly increase production of nitrous oxide, a greenhouse gas, and decrease the habitat of many megafauna. In the subtropical Atlantic Ocean, however, there is an observed oxygen gain that cannot be accounted for by observed warming. We show that the amplification of the hydrological cycle, a response to climate change which results in a ‘salty-get-saltier, fresh-get-fresher’ sea surface salinity pattern, influences deoxygenation patterns in an Earth System Model, and can explain the observed oxygenation. In the Atlantic Ocean, this hydrological cycle amplification leads to enhanced ventilation and oxygenation of ‘salty-get-saltier’ subtropical water masses, while reducing ventilation and oxygen content in ‘fresh-get-fresher’ water masses formed at higher latitudes. The oxygenation of subtropical Atlantic waters is thus shown to be a regional consequence of climate change (through surface salinity changes) even as the global consequence of climate change (directly through warming) is deoxygenation.
1. Introduction

The oceans lose oxygen in response to global warming. This loss is attributed to the rise in ocean temperature, which decreases oxygen solubility and increases upper ocean stratification, thereby weakening the subduction and transport of well oxygenated surface waters into the ocean interior - a process called ocean ventilation (Bopp et al. 2013; Stramma et al. 2008, 2012; Schmidtko et al. 2017; Prince et al. 2010). This ocean deoxygenation has the potential to enhance the production of nitrous oxide, a potent greenhouse gas (Arevalo-Martínez et al. 2015; Babbin et al. 2015; Ji et al. 2018), and compress the habitat of macro-organisms, raising concern for the sustainability of fisheries of highly valuable species such as tuna (Chu and Tunnicliffe 2015; Stramma et al. 2012). Observations and modeling studies suggest that the globally integrated ocean oxygen content has already declined by up to 2% over the last five decades (e.g. Schmidtko et al. 2017; Pörtner et al. 2019), and future projections indicate that this oxygen loss could reach up to 6% in 2100 if emissions are not curtailed (Bopp et al. 2013; Kwiatkowski et al. 2020; Lévy et al. 2022).

The regional patterns of deoxygenation, however, remain highly uncertain and the mechanisms that control them are poorly constrained (e.g. Bopp et al. 2013; Oschlies et al. 2018; Palter and Trossman 2018; Stendardo and Gruber 2012; Claret et al. 2018). For example, observations in the Atlantic Ocean over the last six decades show a strong oxygen loss at high northern latitudes (north of 50°N), consistent with the temperature-driven decrease in solubility and ventilation, but also a counter-intuitive oxygen gain in parts of the subtropical subsurface Atlantic (10-30° latitude, 200-1000 m depth) which remains unexplained (Ito et al. 2017; Helm et al. 2011; Stendardo and Gruber 2012). In this study, we show that the hydrological cycle amplification, a response to global warming that reinforces evaporation and precipitation patterns (Held and Soden 2006), contributes to the observed oxygen changes in the Atlantic Ocean. Specifically, we find that the changes in sea surface salinity associated with these evaporation and precipitation changes alter the oceanic supply of oxygen by ventilation, and can explain the oxygen gain observed in the subtropics and the intensification of oxygen loss further north.

Observations (in-situ and satellite) and observation-based reanalyses show that mean sea surface salinity (SSS) patterns have intensified globally in recent decades (e.g. Durack et al. 2012; Olmedo et al. 2022). In the Atlantic Ocean, latitudinal SSS gradients have amplified. The already salty surface waters in the subtropics (~10-35°) have become saltier, while the fresher surface waters
Fig. 1. Salinity and oxygen concentration along a mid-Atlantic Ocean depth-section derived from observations and in the ESM2M model. (a) Mean salinity from observation-based reanalysis ORAS5. (b) Mean oxygen concentration from the World Ocean Atlas 2018 (Garcia et al. 2019). Visual above (a, b) describes ‘salty-get-saltier’ and ‘fresh-get-fresher’ patterns. (c, e) Salinity trends from ORAS5 (1958-2017) and ESM2M Standard 1% experiment (200-year trend, five-member ensemble mean). (d, f) Oxygen trends from the observation-based product of Ito et al. (2017) (1950-2016 trend where at least 20 points are available; hatched where significance does not exceed 25%), and ESM2M Standard 1% experiment (200-year trend, five-member ensemble mean). Section is at 25°W and extends into the Labrador Sea (see inset map next to a). Black lines water masses, defined in Methods; stippled region indicates Bottom Waters which we exclude from this study’s analysis.

at higher latitudes (poleward of ∼40°) have experienced a decrease or near-zero change in SSS (Figure 1a,c). These SSS changes have been attributed to the hydrological cycle amplification, i.e., the amplification of the precipitation minus evaporation pattern (see schematic over Figure 1a,b). Climate models robustly project this amplification of the hydrological cycle with global warming
(specifically, amplified moisture convergence in the atmosphere requires an amplification of surface moisture flux; Held and Soden 2006). This mechanism explains the SSS changes observed in the Atlantic Ocean as it causes salty regions, where climatological evaporation exceeds climatological precipitation, to become saltier, and fresh regions, where precipitation exceeds evaporation, to become fresher (e.g. Bindoff et al. 2019, Figure 1a). As evidenced by the observation-based Ocean ReAnalysis System 5 (ORAS5, Zuo et al. (2019)), this surface freshwater forcing propagates into the ocean interior and imprints on the four main water masses that ventilate the Atlantic Ocean interior (water masses shown by black contours and arrows in Figure 1). The salty Tropical and Mode Waters, which are formed in the tropics and subtropics and supply oxygen to the surface and subsurface down to 500-1000 m depth, have become saltier (Figure 1 a,c). In contrast, the fresher Intermediate and Deep Waters, which are formed at higher latitudes and supply oxygen to the deep ocean underneath Tropical and Mode Waters, have become fresher or experienced marginal changes in salinity (Figure 1 a,c).

These changes in salinity influence water masses’ density, and therefore their formation rate, subduction and transport into the ocean interior. In particular, the strong increase in salinity in the subtropical Atlantic was shown to efficiently de-stratify the surface layer despite the warming-driven stratification in a global climate model (Liu et al. 2021), which could potentially lead to deeper mixed layers and enhanced ventilation of the subsurface ocean by Mode Waters. At higher latitudes, the surface freshens (Brewer et al. 1983; Curry et al. 2003; Durack et al. 2012; Yashayaev 2007; Read and Gould 1992; Dickson et al. 2002), enhancing warming-driven stratification and potentially weakening the ventilation of deeper layers by Intermediate and Deep Waters (Drijfhout et al. 2012; Cheng et al. 2013; Fan et al. 2021; Zhu and Liu 2020; Stouffer et al. 2006). The amplification of the hydrological cycle and the associated surface salinity changes could therefore alleviate the warming-driven deoxygenation in salty water masses but reinforce it in fresher water masses.

Here, we use a global Earth System model (ESM2M) to quantify the effect of amplified SSS patterns on Atlantic Ocean deoxygenation. We compare a ‘Standard’ warming experiment in which the model evolves freely and SSS patterns amplify in response to atmospheric CO\textsubscript{2} increase (1% yr\textsuperscript{-1} CO\textsubscript{2} increase until doubling, then held constant for a total of 200 simulation years), to a ‘Fix-SSS’ experiment in which the same CO\textsubscript{2} increase is prescribed but SSS patterns do not
respond and are instead restored to their pre-industrial climatological values (similarly to Liu et al. 2021, see details in Methods). While warming occurs in both experiments, the influence of the hydrological cycle amplification only occurs in the Standard experiment (and not in Fix-SSS). In this comparison, we emphasize the contrast between the two saltier Atlantic water masses (Tropical and Mode) and the two fresher water masses (Intermediate and Deep), and establish a mechanistic link between hydrological cycle amplification, salinity changes, and pattern of ocean deoxygenation.

2. Salinity and oxygen track Atlantic ventilation changes

We compare the response to climate change (or ‘climate effect’) in the ESM2M model (200-year trend averaged across five ensemble members of the Standard experiment) and the observation-based products (1950s-2010s trends) along a mid-Atlantic section that extends into the Labrador Sea and captures the pathways of the four main Atlantic water masses (Tropical, Mode, Intermediate, Deep; Figure 1). The ESM2M model reproduces the propagation of the surface salty-get-saltier and fresh-get-fresher signal into the ocean interior seen in the ORAS5 reanalysis, including the increase in salinity of Mode and Tropical Waters formed at tropical and subtropical latitudes where evaporation increases, and the strong freshening of Deep Waters that outcrop at higher northern latitudes where evaporation decreases (Figure 1c,e, see precipitation and evaporation changes in Figure S2). Differences exist, however, between the model and reanalysis. Notably, as the south Atlantic subtropical gyre expands and the boundary between Mode and Intermediate waters moves poleward (a feature supported by satellite and in-situ observations, Drouin et al. 2021; Yang et al. 2020), it redistributes salt meridionally in the model (dipole of salinity change at ~35°S, Figure 1e), but has no apparent effect on salinity in the reanalysis (Figure 1c).

Oxygen trends derived from the observation-based oxygen product of Ito et al. (2017) are limited to parts of the upper 1000 m due to sparse data coverage and are often not statistically significant (Figure 1d). Yet, we find encouraging agreement between this dataset and the model. Both suggest a widespread oxygen loss along the mid-Atlantic section, but also pockets of oxygen gain in Mode and Deep Waters despite a general warming of these water masses (Figure 1d,f, see warming trends in Supplementary Material and Figure S1). The patchiness of the observed and simulated oxygen changes shows that competing mechanisms are at play, and highlights the challenges associated
Fig. 2. Salty-get-saltier waters lose less oxygen than fresher waters experiencing near-zero salinity changes. (a) Oxygen change vs. salinity change due to total climate effect ($\Delta S_{\text{Clim}}$, and $\Delta O_{2\text{Clim}}$ corresponding to trends in Standard experiment) and (b) oxygen change due to hydrological effect alone ($\Delta O_{2\text{Hydro}}$, difference between trends in Standard and Fix-SSS experiments) vs salinity change due to total climate effect ($\Delta S_{\text{Clim}}$). Colors represent the mean salinity in the pre-industrial control experiment. Both panels show $\Delta S_{\text{Clim}}$ for consistency but note that the salinity trend due to the hydrological effect ($\Delta S_{\text{hydro}}$) is nearly identical to $\Delta S_{\text{Clim}}$. Points represent 200-year trends, averaged within each water mass and across five ensemble members; error bars represent the range across the ensemble members.

with the quantification of ocean deoxygenation at each individual point in space. In the following, we employ the water mass framework that follows the ventilation pathways of the four main Atlantic water masses to link changes in hydrological cycle amplification, salinity, and oxygen.

3. Stronger deoxygenation in fresher water masses

When averaged over the full Atlantic basin, fresher water masses (Intermediate and Deep Waters) experience stronger deoxygenation and weaker salinity increase than saltier water masses (Tropical and Mode Waters) in response to climate change in the ESM2M model (‘climate effect’ $\Delta S_{\text{Clim}}$ and $\Delta O_{2\text{Clim}}$, Figure 2 a). Salty Mode Waters become saltier and avoid deoxygenation ($\Delta S_{\text{Clim}} = +0.020$ [0.015 to 0.022] psu decade$^{-1}$, $\Delta O_{2\text{Clim}} = -0.03$ [-0.08 to +0.05] $\mu$mol kg$^{-1}$ decade$^{-1}$; mean and range of five ensemble members, see Figure 2a and Methods). This small simulated net change in oxygen is due to the opposing oxygenation and deoxygenation trends within the water mass, a result consistent with the observation-based product of Ito et al. (2017) and prior studies (Figure 1 d,f
Stendardo and Gruber 2012; Helm et al. 2011). Tropical Waters also become saltier but at a lower rate than Mode Waters ($\Delta S_{\text{Clim}} = 0.015 \ [0.013 \text{ to } 0.017] \ \text{psu decade}^{-1}$) and slightly lose oxygen ($\Delta O_{2\text{Clim}} = -0.28 \ [-0.29 \text{ to } -0.27] \ \mu\text{mol kg}^{-1} \ \text{decade}^{-1}$, Figure 2a). In contrast, fresh Intermediate and Deep waters are characterized by the weakest salinity changes ($\Delta S_{\text{Clim}} < 0.007 \ \text{psu decade}^{-1}$, Figure 2a), and the strongest deoxygenation rates ($\Delta O_{2\text{Clim}} = -0.83 \ [-0.87 \text{ to } -0.80] \text{ and } -0.60 [-0.64 \text{ to } -0.53] \ \mu\text{mol kg}^{-1} \ \text{decade}^{-1}$). The lack of a strict ‘fresh-get-fresher’ salinity change in Intermediate and Deep Waters in the model is consistent with the ORAS5 reanalysis (Figure 1c,e) as well as prior observation-based studies (e.g. Durack and Wijffels 2010). The Atlantic Ocean as a whole becomes saltier in contrast to the Pacific Ocean becoming fresher, which pushes surface salinity trends towards higher values across the Atlantic (although it still yields higher trends in saltier waters than fresher waters). In addition, the freshening of Intermediate Waters associated with the precipitation increase at the outcrop surface is offset by significant cross-isopycnal mixing with salty Mode Waters in the ocean interior - a process known to contribute significantly to the mean state and changes in this water mass (Talley 2011; Iudicone et al. 2016) - as well as the southward advection of Mode Waters into Intermediate Waters as the subtropical gyre expands polewards (Figures 1e and 3a).

We isolate the effect of salinity and oxygen changes associated with the hydrological cycle amplification or ‘hydrological effect’ from the total ‘climate effect’ using the difference between the Standard warming experiment and the Fix-SSS experiment in which sea surface salinity is restored towards its pre-industrial values (see Methods). The salinity trends associated with the hydrological cycle amplification ($\Delta S_{\text{Hydro}}$ in Figure 3a) closely match the salinity trends simulated in response to the full climate effect ($\Delta S_{\text{Clim}}$ in Figure 1e). This is consistent with the understanding that salinity trends under climate change are largely attributable to hydrological cycle amplification (Durack et al. 2012). Oxygen changes due to the hydrological effect scale with these salinity changes (Fig 2b). This effect yields a strong oxygen gain in Mode Waters that experience rapid salinification ($\Delta O_{2\text{Hydro}} = +0.44 \ [+0.40 \text{ to } +0.46] \ \mu\text{mol kg}^{-1} \ \text{decade}^{-1}$), a near-zero change in Intermediate and Tropical Waters that experience milder salinification ($\Delta O_{2\text{Hydro}} < +0.10 \ \mu\text{mol kg}^{-1} \ \text{decade}^{-1}$), and a strong oxygen loss in Deep Waters that experience a near-zero salinification ($\Delta O_{2\text{Hydro}} = -0.43 \ [-0.45 \text{ to } -0.39] \ \mu\text{mol kg}^{-1} \ \text{decade}^{-1}$, Figure 2b). The hydrological cycle amplification therefore contributes to the net pattern of deoxygenation due to climate change, by
modulating the amplitude of the oxygen loss due to the direct effect of rising ocean temperature (i.e., stratification increase and solubility decrease). Its impact is strongest in salty Mode Waters, where the oxygen gain due to the hydrological effect counteracts the warming-driven deoxygenation yielding a marginal net change in response to the full climate effect, as well as in fresh Deep Waters, where it accounts for more than half of the net simulated deoxygenation (Figure 2 a-b).

4. Influence of hydrological cycle amplification on ocean circulation and ventilation

The amplification of surface salinity patterns due to the hydrological effect enhances the ventilation of Mode Waters and weakens the ventilation of Deep Waters, by influencing both the depth of winter mixing in outcrop regions, and the strength of the shallow and deep overturning circulations carrying these water masses into the ocean interior. At northern mid-latitudes, where North Atlantic Mode Waters are formed, winter mixed layer depths (MLDs) during the last 50 years of simulation are deeper in the Standard warming experiment than in the Fix-SSS experiment (~50 m deeper along mid-Atlantic section, solid grey line below dashed grey line in Figure 3a,b). This indicates that in these regions the effect of salinification (increases density and destabilizes upper ocean) exceeds the effect of warming (reduces density and stratifies upper ocean, see also Liu et al. 2021). In addition, we find that the transport by the shallow overturning subtropical cells during the last 50 years of simulation is stronger in the Standard warming experiment (15.3 Sv) than in the Fix-SSS experiment (14.1, shallow overturning index calculated as the difference between the maximum of the Atlantic meridional overturning streamfunction between 12°N and 16°N and the minimum between 12°N and 16°S above 200 m depth; adapted from Lohmann and Latif 2005). Together, these results suggest that both the formation and transport into the ocean’s interior of Mode Waters is enhanced by the low- to mid-latitude ‘salty-get-saltier’ pattern.

In contrast, winter MLDs shoal as the surface freshens in regions of Deep Water formation, (solid grey line above dashed grey line in Figure 3a,b). In the Labrador Sea (above 55°N), winter MLDs shoal from 2000 m in the pre-industrial control to 500 m at the end of the Standard warming experiment in response to freshening and warming. This shoaling is less pronounced at the end of the Fix-SSS experiment in which the surface warms but does not freshen, shoaling to only 1000 m (Figure 3a,b), twice as deep as at the end of the Standard warming experiment. This result suggests that the ‘fresh-get-fresher’ effect weakens the formation rate of Deep Waters in the Labrador Sea.
**Fig. 3.** Salinity and oxygen changes in response to hydrological effect along mid-Atlantic Ocean depth section. Trends in (a) salinity and (b) oxygen from the hydrological effect ($\Delta S_{Hydro}$, $\Delta O_{2Hydro}$; 200-year trend in ‘Standard’ warming experiment minus 200-year trend in ‘Fix-SSS’ experiment, each averaged over five ensemble members). Water masses are outlined by black contours (see Methods). Grey lines represent annual maximum mixed layer depths in the last 50 years of each model experiment, with solid representing the Standard experiment and dashed representing the Fix-SSS experiment in both panels. Stippling represents Bottom Waters which we exclude from our analysis. Section is indicated by the black line in inset of Figure 1. Contributions from ventilation ($\Delta O_{2Clim,vent}$) and solubility ($\Delta O_{2Clim,sat}$) changes are shown in Figure S4.

We also find that the strength of the deep Atlantic meridional overturning circulation (AMOC) is slightly weaker in the last 50 years of the Standard experiment than in the Fix-SSS experiment (by 0.6 Sv, AMOC strength estimated as the maximum of the streamfunction between 10 and 60°N over all depths, e.g. Dunne et al. 2012). This slowing down of AMOC is consistent with idealized model ‘hosing’ experiments in which freshwater is added in large volumes to regions of Deep Water formation (Stouffer et al. 2006; Manabe and Stouffer 1995). The difference in AMOC between the two experiments presented here is small, but together with the changes in winter MLDs, it suggests that hydrological cycle amplification slightly reduces the formation rate of Deep Waters in the Atlantic Ocean on centennial timescale.
5. Direct and indirect effects of the hydrological cycle amplification on ocean deoxygenation

Salinity-driven changes in ocean ventilation have a direct impact on ocean oxygen content by modulating the rate at which oxygenated waters are subducted and transported by each water mass, but also indirect effects via oxygen solubility and biological demand. Because hydrological changes slightly alter the ocean circulation, they influence the ocean heat uptake and temperature of the different water masses (Liu et al. 2021), and consequently the oxygen solubility. These changes in circulation and temperature can also modulate biological production and respiration. We can attribute the simulated changes in oxygen in response to the hydrological effect to these three factors, i.e. changes in ventilation ($\Delta O_{2\text{Hydro,vent}}$, dark blue bars in Figure 4b), solubility ($\Delta O_{2\text{Hydro,sat}}$, light blue bars in Figure 4b), and changes in biological activity which we find have a negligible effect here except in Tropical Waters ($\Delta O_{2\text{Hydro,bio}}$, green bars in Figure 4).

The salinity-driven increase in ventilation in Mode Waters (deeper winter mixed layers and stronger shallow overturning circulation; Figure 3b and section 4) also enhances their heat uptake and temperature (Figure S1). The oxygen gain associated with the hydrological effect in Mode Waters ($\Delta O_{2\text{Hydro}} = +0.44 [+0.4 \text{ to } +0.46] \mu\text{mol kg}^{-1} \text{ decade}^{-1}$) therefore arises from the partial compensation between a strong gain tied to enhanced ventilation ($\Delta O_{2\text{Hydro,vent}} = +0.68 [+0.65 \text{ to } +0.71] \mu\text{mol kg}^{-1} \text{ decade}^{-1}$) and a weaker loss tied to solubility changes ($\Delta O_{2\text{Hydro,sat}} = -0.23 [-0.25 \text{ to } -0.20] \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, Figures 2b and 4). In contrast, the hydrological effect weakens the ventilation of Deep Waters (shallower winter mixed layer and slightly weaker AMOC, Figure 3b and section 4) and reduces the temperature of the Labrador Sea (north of 40N in Figure S1). Yet, weakened mixing with very cold Bottom Waters in the Standard experiment (relative to the Fix-SSS) leads to a weak warming of most of the Deep Waters volume, which exceeds the more localized cooling in the formation regions (Figure S1). As a result, these two hydrological effects (ventilation and solubility) yield a loss of oxygen in Deep Waters, with ventilation contributing about 60% ($\Delta O_{2\text{Hydro,vent}} = -0.3 [-0.33 \text{ to } -0.27] \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, $\Delta O_{2\text{Hydro,sat}} = -0.12 [-0.13 \text{ to } -0.12] \mu\text{mol kg}^{-1} \text{ decade}^{-1}$, Figure 4). This compensation in oxygen solubility changes between interior and formation region might be specific to the ESM2M model and should be interpreted with caution. Despite this uncertainty in net solubility changes, ventilation changes control the oxygenation changes due to the hydrological effect in both Mode and Deep Waters.
FIG. 4. Drivers of (de)oxygenation in Atlantic water masses due to the hydrological effect. Oxygen trends attributed to the hydrological effect ($\Delta O_2^{Hydro}$, black outline, as in Figure 2b), separated into contributions from ventilation ($\Delta O_2^{Hydro,vent}$, dark blue), solubility ($\Delta O_2^{Hydro,sat}$, light blue) and biological activity ($\Delta O_2^{Hydro,bio}$, green). $\Delta O_2^{Hydro,bio}$ is only significant in Tropical Waters (2-4 orders of magnitude smaller than the other terms in other water masses). Bars represent 200-year trends, averaged within each water mass and across five ensemble members; error bars represent the range across the ensemble members. The three drivers are shown for the Standard experiment in Figure S3 ($\Delta O_2^{Clim,sat}$, $\Delta O_2^{Clim,vent}$, and $\Delta O_2^{Clim,bio}$).

In the model, the hydrological effect has little or no influence on the oxygenation of Intermediate and Tropical Waters, due to the near complete compensation between the different contributions (ventilation, solubility and biology, Figure 4). In Intermediate Waters, a small decrease in oxygen supply by ventilation ($\Delta O_2^{Hydro,vent} = -0.07 [-0.18 to -0.03] \text{ umol kg}^{-1} \text{ decade}^{-1}$) is entirely opposed by an equally small increase in oxygen solubility ($\Delta O_2^{Hydro,sat} = +0.08 [+0.06 to +0.11] \text{ umol kg}^{-1} \text{ decade}^{-1}$). The small ventilation change simulated here (despite a clear surface freshening, Figure S2) is due to the offsetting effects of the surface freshening, which causes a mild ventilation decrease and oxygen loss over much of the volume of Intermediate Waters, and a smaller volume of strong salinification and oxygenation caused by the poleward advection of, and mixing with, Mode Waters (see section 2, Figure 3e). Similarly, the small solubility change is tied to the surface freshening, which causes a decrease in ocean heat uptake and cooling (but is partly offset by the
intruding and rapidly warming Mode Waters, Figure S1c). In Tropical Waters, the hydrological effect weakens the supply of oxygen by ventilation ($\Delta O_{2\text{Hydro,vent}} = -0.20 [-0.28 to -0.14]$ umol kg$^{-1}$ decade$^{-1}$), but also slightly increases oxygen solubility ($\Delta O_{2\text{Hydro,sat}} = +0.08 [+0.05 to +0.11]$ umol kg$^{-1}$ decade$^{-1}$) and lowers the biological consumption of oxygen (cooling slows respiration, $\Delta O_{2\text{Hydro,biot}} = +0.19 [+0.13 to +0.25]$ umol kg$^{-1}$ decade$^{-1}$). The decrease in ventilation is inconsistent with the stratification change, and is likely due to a slight difference in surface winds. The slight cooling and consequent increase in oxygen solubility at the surface in response to the hydrological effect (i.e. the Standard experiment with hydrological amplification warms less than the Fix-SSS experiment) is balanced by a global increase in ocean heat uptake in subducted water masses (see also Liu et al. 2021; Williams et al. 2007).

6. Conclusion

The patterned change in oxygen in response to the hydrological cycle amplification identified here adds important nuance to the baseline expectation that warming-driven decreases in both solubility and ventilation cause widespread deoxygenation (e.g. Keeling et al. 2010; Bopp et al. 2002, 2013; Stramma et al. 2008; Schmidtko et al. 2017). The oxygenation of Atlantic Mode Waters in response to climate change observed in nature, and previously unexplained (Stendardo and Gruber 2012), can be accounted for by the increase in ventilation of ‘salty-get-saltier’ water masses. In contrast, ‘fresh-get-fresher’ Deep Waters experience weakening ventilation and enhanced deoxygenation.

The exact magnitude of this oxygen redistribution due to hydrological cycle amplification is subject to uncertainty. The increase in salinity in Mode Waters simulated in the model is lower than in the observation-based products (Figure 1c,e). This underestimation of the hydrological cycle amplification and associated low latitude salinification in the model is partly due to the slower warming simulated in the 200-year Standard 1% experiment (global surface warming of 0.1K per decade) relative to the historical period (global surface warming of 0.2K per decade for 1960-2018, Rohde and Hausfather (2020)). As a result, the increase in ventilation and oxygenation associated with the hydrological effect in Mode Waters might be even stronger in nature. In contrast, the simulated freshening of Deep Waters attributed to hydrological cycle amplification in the model might be overestimated, because part of the signal might be associated with the transport
of freshwater originating from sea ice melt in the Arctic (poleward of 80°N; see details on surface salinity restoring in Methods).

We show that changes in SSS associated with the hydrological cycle amplification will affect future regional Atlantic Ocean oxygen changes as much as warming. In other ocean basins, SSS will also affect surface seawater density, and impact ocean stratification and ventilation. Projected SSS changes in the Pacific and Indian Oceans are, however, weaker than in the Atlantic (Durack and Wijffels 2010), so the contribution to oxygen changes is expected to be weaker in those basins. On the century timescales considered here, the hydrological cycle amplification is the main driver of salinity changes. On longer timescales, ice sheet melt would reinforce the freshening (e.g. Pauling et al. 2016) and potentially further weaken the ventilation and oxygenation of the deep water masses formed at high latitudes.

7. Methods

a. Model and Experimental Setup

We isolate the effect of hydrological cycle and SSS pattern amplification using two idealized ensemble experiments in the Geophysical Fluid Dynamics Laboratory (GFDL) Earth System Model, version 2M (ESM2M; source code is based on public release 5.0.2 and can be downloaded at github.com/mom-ocean/MOM5) (Dunne et al. 2012, 2013). This version uses the Modular Ocean Model 5 (MOM5) with nominal 1 degree resolution (telescoping to 1/3 degree at the equator), Atmospheric Model 2 (AM2) with 2x2.5 degree resolution, Land Model 3 (LM3.0), and the Tracers of Ocean Phytoplankton with Allometric Zooplankton (TOPAZ) biogeochemical module (full description in the supplemental material of Dunne et al. 2013). The model is initialized with a multicentury run from the same model, then spun up for approximately 200 model years with constant pre-industrial atmospheric CO$_2$ of 286 ppm. Drift in both physical and biogeochemical variables, estimated from the pre-industrial control run, are within the targets outlined in Dunne et al. (2013). Specifically, global mean SST and SSS have no apparent drift (variability is within +/- 0.2 K and +/-0.02 psu), the global mean ocean temperature drifts by about 0.01 °C per century, and globally integrated oxygen content drifts by less than 1% per century. Linear drifts derived from the control run are removed from our results at each grid point.
Two transient ensemble climate change experiments are initialized from the spin-up: Standard and fixed sea surface salinity (Fix-SSS). In the Standard experiment, the atmospheric CO$_2$ concentration is increased at 1% per year until the CO$_2$ concentration doubles at year 70, after which the concentration is held fixed for 130 years, so the model run is 200 years long. The ‘Fix-SSS’ experiment is similar to the Standard run but SSS is nudged towards the pre-industrial climatology with a freshwater restoring flux (linear in time, with a 30-day timescale). Since the focus here is on changes in precipitation-evaporation tied to the hydrological cycle amplification, SSS is not restored at locations with seasonal sea ice (Figure S5 and supplemental text). Freshwater from sea ice melt that has been transported and led to freshening outside of the region of seasonal sea ice would be restored and attributed to the hydrological cycle amplification in our setup. This could slightly exaggerate the freshening and consequent impacts in the high latitude North Atlantic. However, our results suggest that the freshening in this region is due to a decrease in evaporation (Figure S2) associated with the cooling due to AMOC slowdown and that freshwater flux trends due to ice melt are relatively small.

The Standard experiment is used to quantify the total effect of climate change on ocean oxygen, which includes the effect of warming, the amplification of the hydrological cycle, as well as other forced changes in the earth system (e.g. sea ice melt, winds, circulation changes). Note that the freshening at polar latitudes is likely underestimated since ESM2M does not incorporate an interactive ice sheet model. The effect of hydrological cycle amplification is quantified by the difference between the Standard and Fix-SSS experiments. The total climate effect and hydrological effect are designated as $\Delta X_{\text{Clim}}$ and $\Delta X_{\text{Hydro}}$ for any variable X. For example, $\Delta S_{\text{Hydro}}$ is positive where the ocean gets saltier as the climate system warms, and negative where the ocean gets fresher.

To reduce the impact of internal variability in the model solutions, we run five ensemble members for each experiment branched from different years in the pre-industrial control spinup experiment (branched from spinup years 190, 191, 192, 194 and 196). Results are shown for the Atlantic Ocean using the mask shown in Figure S5. Model trends are computed over 200 model years (including the 70 years of CO$_2$ increase and another 130 years of constant CO$_2$ at 586ppm) in each member (after removing drift), and then averaged over the five members.
b. Atlantic Water Mass Definition

We define Atlantic water masses with density and salinity thresholds based on Talley (2011) but slightly adjusted for mean model bias (Figure 1e,f). Tropical Waters are defined as all waters lighter than 1025 kg m\(^{-3}\). Mode Waters are further delimited as saltier than 35 psu and lighter than 1027.7 kg m\(^{-3}\), while Intermediate Waters are fresher than 34.4 psu and lighter than 1027.7 kg m\(^{-3}\). Mode Waters here include northern and southern subtropical Mode Waters, as well as subpolar Mode Waters in the north Atlantic. Deep Waters include Upper Deep Waters, which are relatively light and can be found between Intermediate and Mode Waters, as well as waters denser than 1027.7 kg m\(^{-3}\). Finally, we remove Bottom Waters based on a threshold of potential density referenced to 2000 dbar (\(\rho_2\)) of 1036.82 kg m\(^{-3}\). The water mass definitions are stationary in time, determined by the time-mean physical sea state in the 200 year pre-industrial control run.

In the observation-based data products, the relevant thresholds in salinity and density are not the same as in the model (which is, for example, biased slightly fresh relative to observations throughout the Atlantic Ocean) but match the observation-based definitions given by Talley (2011) (Figure 1a-d). Tropical Waters are, again, all waters lighter than 1025 kg m\(^{-3}\). Mode Waters in the reanalysis, however, are defined to be saltier than 36.1 psu, warmer than 8°C, and lighter than 1027.7 kg m\(^{-3}\), while Intermediate Waters are fresher than 34.25 psu and lighter than 1027.7 kg m\(^{-3}\). Deep Waters include the remaining volume between and denser than Mode and Intermediate Waters, but lighter than \(\rho_2 = 1037\) kg m\(^{-3}\). Water denser than this is considered Bottom Water.

c. Drivers of \(O_2\) changes

We attribute the changes in oxygen to changes in the saturated oxygen concentration (\(O_{2, sat}\)), which is primarily reflective of warming, changes in biological consumption or production of oxygen (\(O_{2, bio}\)), and changes in ventilation (\(O_{2, vent}\)).

\[ \Delta O_2 = \Delta O_{2, sat} + \Delta O_{2, bio} + \Delta O_{2, vent} \]

\(O_{2, sat}\) is calculated from monthly-mean conservative temperature and salinity. \(O_{2, bio}\) is provided by the biogeochemical module of ESM2M (TOPAZ), and \(O_{2, vent}\) is derived as the residual. This is very similar to the ‘Apparent Oxygen Utilization’ methodology (e.g. Lévy et al. 2022; Boyer et al.}
1999; Kester and Pytkowicz 1968), which groups the effects of biology and circulation together for applications where the impact of biology is unknown.
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References


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